Complete characterization of optical pulses by real-time spectral interferometry

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We demonstrate a simple method for complete characterization (of amplitudes and phases) of short optical pulses, using only a dispersive delay line and an oscilloscope. The technique is based on using a dispersive delay line to stretch the pulses and recording the temporal interference of two delayed replicas of the pulse train. Then, by transforming the time domain interference measurements to spectral interferometry, the spectral intensity and phase of the input pulses are reconstructed, using a Fourier-transform algorithm. In the experimental demonstration, mode-locked fiber laser pulses with durations of ~1 ps were characterized with a conventional fast photodetector and an oscilloscope.

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1. Introduction

As optical pulses are becoming shorter and have wide use for many basic and applied purposes, there is a strong need for simple and quick measurement techniques. Indeed, a variety of methods were developed throughout the years for what is called complete characterization, for finding the amplitudes and the phases of optical pulses. A widely used pulse measuring method is frequency-resolved optical gating (see, for instance, the reviews in Refs. 1 and 2), which belongs to the class of nonlinear methods. Other techniques that include linear interferometric measurements in the spectral,[3–5] spectral–temporal,[6,7] time,[8,9] and spatial–spectral[10,11] domains or spectral filtering[12] provide simple and direct (i.e., noniterative) processing of the results and much higher sensitivity. Nonetheless, most of those linear techniques have nonlinear ingredients, such as cross-correlation recording,[6,8] nonlinear frequency shear in spectral phase interferometry for direct electric-field reconstruction,[5] or frequency-resolved optical gating for characterizing a reference pulse.[4] Additionally, they require special equipment, for instance, for tunable filtering of the pulse harmonics.[12]

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In the present paper we propose a novel method for complete characterization of optical pulses that is entirely linear and simple to implement. This method is similar to spectral shearing interferometry,[5] but the interference is formed in the time domain and then translated to the spectral domain, owing to the linear relation between the patterns in the temporal and the frequency domains. We call this method real-time spectral interferometry. Because the pulse characterization is performed in the spectral domain, there is no need of high temporal resolution, and thus we were able to characterize fiber laser pulses of ~1 ps by using a conventional fast photodetector and an oscilloscope.

2. Description of the Method

We start with stretching of the optical pulses to be characterized by a dispersive delay line. First, let us assume that this dispersive element has a quadratic phase response and choose line length L to meet the condition $L \gg \tau^2/(8\pi\beta_2)$, where τ is the original pulse width and β_2 is the group-velocity dispersion. Then the output pulse's shape is the temporal analog of the spatial Fraunhofer diffraction[13]:

$$E_{\text{out}}(t) \propto \exp\left[it^2/(2\beta_2 L)\right]F(t/\beta_2 L), \tag{1}$$

where $F(\omega) = |F(\omega)|\exp[i\varphi(\omega)]$ is the complex spectrum of the pulse to be measured and $|F(\omega)|^2$ and $\varphi(\omega)$ are the spectral intensity and the spectral phase of the input pulse, respectively.

According to relation (1), measured intensity $|E_{\text{out}}(t)|^2$ of the stretched pulse gives spectral intensity $I(\omega)$

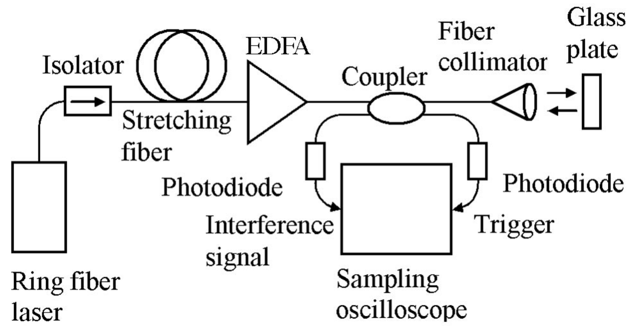

Fig. 1. Schematic representation of the measurement setup. EDFA, erbium-doped fiber amplifier.

$= |F(\omega)|^2$ of the input pulse after a substitution:

$$t = \beta_2 L\omega, \tag{2}$$

where ω is measured relative to the center of the spectrum. Such real-time spectral analysis of optical pulses was performed with an optical fiber[14] or a chirped fiber Bragg grating[15,16] used as a dispersive delay line. However, relation (1) also contains information on the pulse's spectral phase $\varphi(\omega)$ that can be extracted by conventional interferometric measurements. We use for that extraction the method of shearing interferometry, next described.

The stretched pulses are reflected from two sides of a glass plate (see Fig. 1), and the interference between the two reflected replicas is measured by a photodiode and a sampling oscilloscope. It is significant here that the interferometry is performed in the time domain and then transformed to spectral interferometry, according to time-to-frequency conversion [Eq. (2)]. Then the nonlinear frequency shear of Ref. 5 is replaced in our method by linear operation of the temporal delay between the two reflected replicas of the pulses.

The interference intensity is given by

$$I_{\mathrm{int}}(t) = I(\omega) + I(\omega + \Delta\omega) + 2[I(\omega)I(\omega + \Delta\omega)]^{1/2}\cos[\Delta\omega t + \Delta\varphi(\omega)], \tag{3}$$

where

$$\Delta\varphi(\omega) = \varphi(\omega + \Delta\omega) - \varphi(\omega) \approx (\mathrm{d}\varphi/\mathrm{d}\omega)\Delta\omega \tag{4}$$

and ω and frequency shear $\Delta\omega$ are related to t and to time delay Δt in the glass plate by Eq. (2). The spectral phase can be obtained from relation (4):

$$\varphi(\omega) = (1/\Delta\omega)\int \Delta\varphi(\omega)\mathrm{d}\omega. \tag{5}$$

Spectral intensity $I(\omega)$ and spectral phase $\varphi(\omega)$ can be obtained from the measured spectral interferogram by use of relations (3)–(5), as shown below. Then by a Fourier transform we obtain the reconstructed time-dependent quantities, $I(t)$ and $\varphi(t)$, of the original pulse.

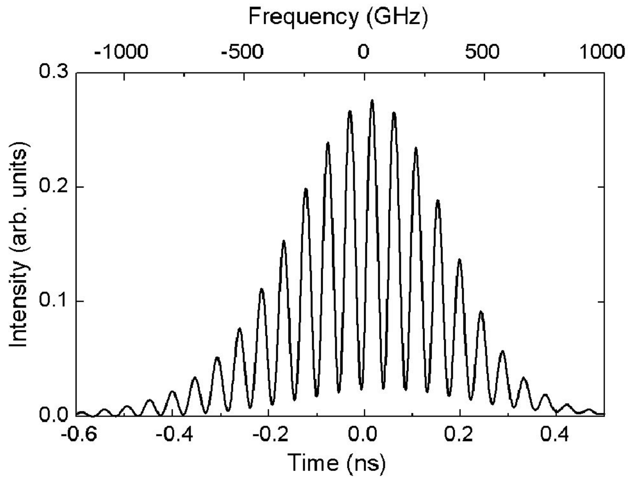

Fig. 2. Oscilloscope trace of the interference between two replicas of the stretched pulse reflected from the two surfaces of a glass plate. The time and frequency scales are related by Eq. (2).

It is important to emphasize the fundamental difference between our method and that presented in Ref. 9. There too the pulse stretching in a dispersive delay line is used. However, the stretched pulses are first completely characterized there in the time domain, whereas in our method the original pulses are completely characterized in the spectral domain.[5] To characterize the pulse completely in the time domain, one should sample it, according to the sampling theorem, with temporal resolution $\delta t_t \approx 1/f_p$, where f_p is the spectral interval of the nonzero pulse energy. If the temporal resolution of an oscilloscope is insufficient for the measurement of the original pulses, stretching of the original pulses cannot improve this situation, because the original and stretched pulses have the same energy spectrum and, therefore, the same temporal resolution is required for their characterization. According to the sampling theorem, spectral resolution δf, required for the pulse characterization in the spectral domain (in our method), is equal to $\delta f \approx 1/\tau_p$, where τ_p is the temporal interval during which the pulse has nonzero energy. Taking into account Eq. (2), we obtain the temporal resolution required for the real-time spectral interferometry:

$$\delta t_s \approx 2\pi\beta_2 L/\tau_p. \tag{6}$$

It is shown below that the needed temporal resolution is readily provided by a conventional fast oscilloscope.

3. Experimental Results

We used an erbium-doped fiber ring laser with passive mode locking for the optical pulse source. The laser generated optical pulses with a repetition rate of 10 MHz at a wavelength of 1530.2 nm. The dispersive delay line was a fiber with high dispersion, commonly used for dispersion compensation. Figure 2 shows the experimental temporal interferogram,

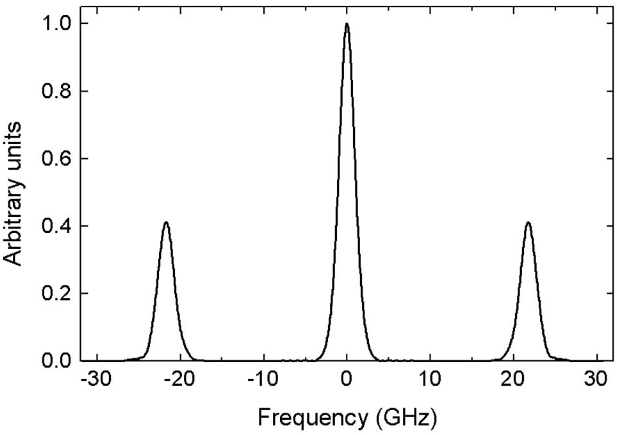

Fig. 3. Absolute value of the Fourier transform of the interference pattern shown in Fig. 2.

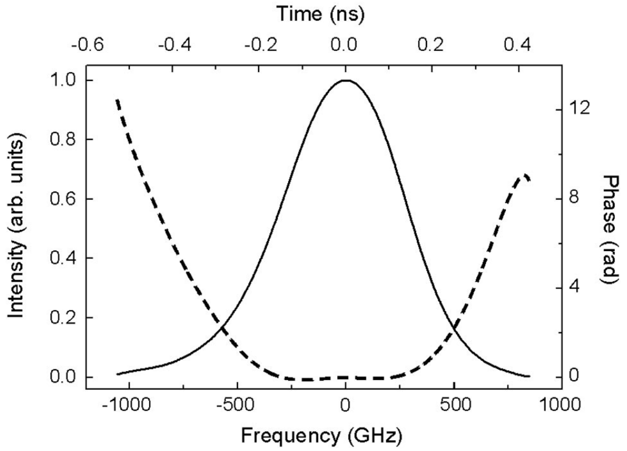

Fig. 4. Spectral intensity $I(\omega)$ (solid curve) and spectral phase $\varphi(\omega)$ (dashed curve) of the input pulse, reconstructed from Fig. 3. The time and frequency scales are related by Eq. (2).

measured with a photodiode and an oscilloscope (both with a bandwidth of 50 GHz. The frequency scale, calculated according to Eq. (2), is also shown in Fig. 2.

We used a phase retrieval procedure similar to that described in Ref. 17. First, the Fourier transform of the interference pattern was calculated, as shown in Fig. 3. Then the pattern of the Fourier transform was shifted to the left by an amount $\Delta\omega/2\pi$. This corresponds to eliminating the linear component $\Delta\omega t$ of the phase difference in Eq. (3). The central and left sidebands were filtered out, and the remaining sideband was inverse Fourier transformed. The absolute value and argument of the signal obtained give, respectively, spectral intensity $I(\omega)$ [we neglect $\Delta\omega$ in $I(\omega + \Delta\omega)$] and phase difference $\Delta\varphi(\omega)$. Spectral phase $\varphi(\omega)$ was calculated by integration, according to Eq. (5).

In reality, the spectral phase response of a dispersive delay line such as an optical fiber is not exactly quadratic. However, we took this deviation into account in our calculation. We considered that the real-time spectral analysis is accomplished in this case only by the quadratic component of the phase response for the pulse that has the so-called distorted complex spectrum $|F(\omega)|\exp[i\varphi(\omega) + i\theta_{\mathrm{nq}}(\omega)]$, where $\theta_{\mathrm{nq}}(\omega)$ is the nonquadratic contribution of phase response $\theta(\omega)$ (the linear part can be neglected). For this case the temporal Fraunhofer condition has to be met for this distorted pulse. Component $\theta_{\mathrm{nq}}(\omega)$ was measured and subtracted from the spectral phase obtained by the procedure described above.

The measurement of phase response $\theta(\omega)$ of the dispersive delay line was done in the same manner as for the pulse's spectral phase. For that purpose, we placed an additional dispersive delay line before the former line. Then $\theta(\omega)$ is given by the difference of the spectral phases obtained in the two measurements, one with both dispersive elements and the second with the additional line only. From the fitting of the experimental data we obtained $\theta(\omega) \approx -4.60 \times 10^{-23}\,\omega^2 + 7.16 \times 10^{-38}\,\omega^3 - 2.066 \times 10^{-51}\,\omega^4$. Note that dispersion and dispersion slopes were measured by a similar method by Dorrer.[18]

The calibration of time delay Δt in the glass plate was made by use of spectral interferometry with a broadband light source (amplified spontaneous emission from an erbium-doped fiber amplifier). The light reflected from two sides of the glass plate was analyzed by an optical spectrum analyzer with a resolution of 0.015 nm. The Fourier transform of the spectral interferogram was calculated as a function of frequency. The position of the sideband peak on the time axis in the Fourier transform corresponds to time delay Δt. The measured value of Δt was 12.51 ps.

The measured spectral intensity $I(\omega)$ (solid curve) and spectral phase $\varphi(\omega)$ (dashed curve) of the original laser pulse are shown in Fig. 4. The relation between the frequency and the time scales in this figure is given by Eq. (2). Figure 5 shows the intensity (solid curve) and the phase (dashed curve) of the fiber laser pulse calculated by the Fourier transform of the pulse spectrum shown in Fig. 4. The pulse width is 1.3 ps.

To test our method we measured the spectral phase response of a 9 m long standard single-mode fiber and compared with a direct group-delay measurement that needs a much longer fiber, for which we used

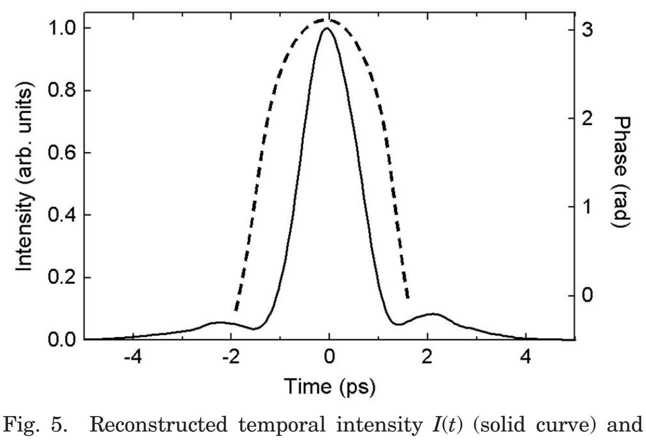

Fig. 5. Reconstructed temporal intensity $I(t)$ (solid curve) and phase $\varphi(t)$ (dashed curve) of the fiber laser pulse.

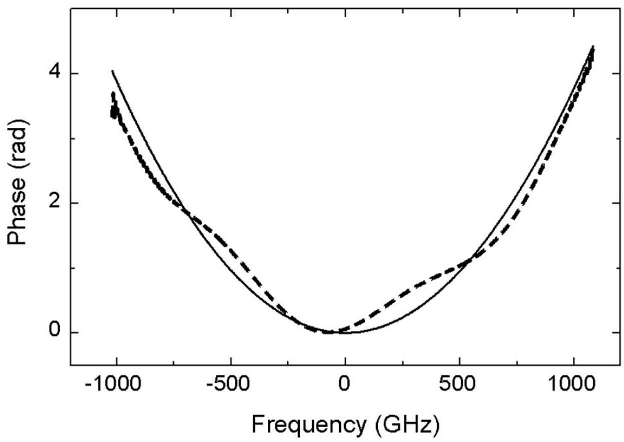

Fig. 6. Measurements of the phase response of a 9 m long conventional fiber obtained by our method (dashed curve) as well as by measuring the frequency dependence of the group delay (solid curve).

20 km of the same fiber. The results of the two measurements are shown in Fig. 6. The average deviation between them was 0.25 rad. We also measured the autocorrelation of the laser pulse and compared it with that calculated for the reconstructed pulse intensity shown in Fig. 5. The results of this comparison are presented in Fig. 7. It can be seen that the agreement between the two curves is excellent.

To estimate the required temporal resolution we use Eq. (6). It should be taken into account that τ_p in relation (6) is the duration of the original pulse, distorted by the nonquadratic component of the dispersion. We estimate that in our experiments $\tau_p \approx 10$ ps and the spectral resolution is $\delta f \approx 100$ GHz, which corresponds to a required temporal resolution of 58 ps. To use the Fourier-transform algorithm we chose a spectral shear of 21.6 GHz (~3% of the pulse's bandwidth), which corresponds to a temporal resolution of 12.5 ps. Such accuracy is provided by a 50 GHz oscilloscope (the accuracy of the time base of our oscilloscope was 7 ps). For comparison, to characterize a

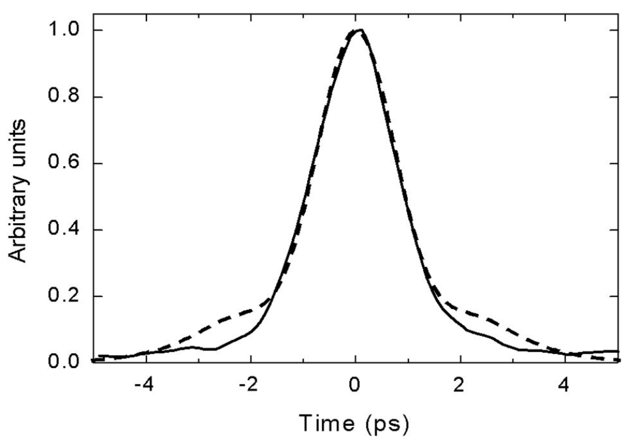

Fig. 7. Autocorrelation of the laser pulse, measured (solid curve) and calculated (dashed curve) for the reconstructed pulse intensity shown in Fig. 5.

pulse of ~1 ps in the time domain, the temporal resolution of an oscilloscope should be less than 0.5 ps (for Gaussian pulses).

It is clear that in our method the stretched pulses should not overlap. This imposes a certain limitation on the maximal repetition rate of the measured pulse trains. Thus the pulse characterization is suitable for fiber lasers with pulse repetition rates of tens or hundreds of megahertz. However, it was shown in Ref. 19 that the interference between stretched overlapping pulses can also be used for pulse characterization. In this way the method in the present paper can be expanded for characterization of high-repetition-rate pulse trains.

4. Conclusions

We have demonstrated a novel method for optical pulse characterization in which spectral interferometry is performed in the time domain. The method is simple and requires only the use of a dispersive delay line and a conventional oscilloscope. The advantage of the method is that the frequency shear that is used in conventional spectral interferometry is replaced in our method by a simple operation of the temporal delay between two replicas of the stretched pulse train. Our method does not require high resolution for temporal measurements and still permits characterization of ~1 ps pulses with a conventional fast photodetector and an oscilloscope.

References

1. R. Trebino, K. W. DeLong, D. N. Fittinghoff, J. N. Sweetser, M. A. Krumbügel, B. A. Richman, and D. J. Kane, "Measuring ultrashort laser pulses in the time–frequency domain using frequency-resolved optical gating," Rev. Sci. Instrum. **68,** 3277–3295 (1997).
2. J. M. Dudley, L. P. Barry, J. D. Harvey, M. D. Thomson, B. C. Thomsen, P. G. Bollond, and R. Leonhardt, "Complete characterization of ultrashort pulse sources at 1550 nm," IEEE J. Quantum Electron. **35,** 441–450 (1999).
3. V. Wong and I. A. Walmsley, "Analysis of ultrashort pulse-shape measurement using linear interferometers," Opt. Lett. **19,** 287–289 (1994).
4. D. N. Fittinghoff, J. L. Bowie, J. N. Sweetser, R. T. Jennings, M. A. Krumbügel, K. W. DeLong, R. Trebino, and I. A. Walmsley, "Measurement of the intensity and phase of ultraweak, ultrashort laser pulses," Opt. Lett. **21,** 884–886 (1996).
5. C. Iaconis and I. A. Walmsley, "Spectral phase interferometry for direct electric-field reconstruction of ultrashort optical pulses," Opt. Lett. **23,** 792–794 (1998).
6. K. C. Chu, J. P. Heritage, R. S. Grant, K. X. Liu, A. Dienes, W. E. White, and A. Sullivan, "Direct measurement of the spectral phase of femtosecond pulses," Opt. Lett. **20,** 904–906 (1995).
7. S. Prein, S. Diddams, and J.-C. Diels, "Complete characterization of femtosecond pulses using an all-electronic detector," Opt. Commun. **123,** 567–573 (1996).
8. J. E. Rothenberg and D. Grischkowsky, "Measurement of optical phase with subpicosecond resolution by time-domain interferometry," Opt. Lett. **12,** 99–101 (1987).
9. R. M. Fortenberry, W. V. Sorin, H. Lin, S. A. Newton, J. K. Andersen, and M. N. Islam, "Low-power ultrashort optical pulse characterization using linear dispersion," in *Optical Fiber Communication Conference,* Vol. 6 of 1997 OSA Technical Digest Series (Optical Society of America, 1997), pp. 290–291, paper ThL3.

10. D. Meshulach, D. Yelin, and Y. Silberberg, "Real-time spatial-spectral interference measurements of ultrashort optical pulses," J. Opt. Soc. Am. B **14,** 2095–2098 (1997).
11. N. K. Berger, B. Levit, and B. Fischer, "Optical pulse intensity and phase measurement by time-to-space conversion based on time-lens operation," Electron. Lett. **37,** 1033–1034 (2001).
12. P. Kockaert, J. Azaña, L. R. Chen, and S. LaRochelle, "Full characterization of uniform ultrahigh-speed trains of optical pulses using fiber Bragg gratings and linear detectors," IEEE Photon. Technol. Lett. **16,** 1540–1542 (2004).
13. A. Papoulis, "Pulse compression, fiber communications, and diffraction: a unified approach," J. Opt. Soc. Am. A **11,** 3–13 (1994).
14. Y. C. Tong, L. Y. Chan, and H. K. Tsang, "Fibre dispersion or pulse spectrum measurement using a sampling oscilloscope," Electron. Lett. **33,** 983–985 (1997).
15. M. A. Muriel, J. Azaña, and A. Carballar, "Real-time Fourier transformer based on fiber gratings," Opt. Lett. **24,** 1–3 (1999).
16. N. K. Berger, B. Levit, A. Bekker, and B. Fischer, "Real-time optical spectrum analyser based on chirped fibre Bragg gratings," Electron. Lett. **36,** 1189–1191 (2000).
17. M. Takeda, H. Ina, and S. Kobayashi, "Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry," J. Opt. Soc. Am. **72,** 156–160 (1982).
18. C. Dorrer, "Chromatic dispersion characterization by direct instantaneous frequency measurement," Opt. Lett. **29,** 204–206 (2004).
19. N. K. Berger, B. Levit, and B. Fischer, "Complete characterization of optical pulses using a chirped fiber Bragg grating," Opt. Commun. **251,** 315–321 (2005).